

Gender differences in spectral and entropic measures of erector spinae muscle fatigue

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Abstract—Electromyographic power spectral analysis is a valuable measurement; however, conflicting results have been reported for amplitude and frequency changes during a fatiguing submaximal muscle contraction. This study compared gender differences for two analyses in subjects with low back pain (LBP). Distinct gender differences are found in musculoskeletal illness/dysfunction, and we examined the effect of gender on entropy and median frequency (MF) slope in a cohort of subjects with LBP. A total of 44 subjects (24 female and 20 male) completed the modified Sorenson test. These subjects ranged in age from 26 to 64 years old, with an average age of 49.9 \pm 9.4 years. Overall, a significant fatigability difference was found based on MF slope ($F = 21.33$, $p = 0.001$) and entropy measures ($F = 68.26$, $p = 0.001$) of the back muscles. While the MF slope was not different ($F = 0.44$, $p = 0.51$) between genders, the entropy values were higher for the male subjects than for the female subjects ($F = 6.70$, $p = 0.01$). These results indicate that the Shannon entropy measure differentiates between genders. Further studies are needed to evaluate the effectiveness of using nonlinear analysis as a measurement tool.

Key words: electromyography, entropy, erector spinae, fatigability, gender, low back pain, median frequency, muscle fatigue, nonlinear time series, rehabilitation.

INTRODUCTION

Several research studies consistently suggest that males and females differ with respect to the prevalence of chronic musculoskeletal pain and that females are more vulnerable to experiencing pain episodes with greater frequency than men [1–4]. Males and females might experi-

ence different pain-generating pathways; therefore, gender-related measurements should be investigated when considering methods that reduce the risk of injury or aggravation of an existing injury [5–6]. However, entropy measurements based on nonlinear time series between genders are not well documented, and a reliable measurement of gender differences is poorly understood. In addition, conflicting results have been reported regarding back muscle fatigability between genders [7–9].

Power spectrum analysis of the surface electromyography (sEMG) signal provides an objective and noninvasive method for assessing low back pain (LBP). During a fatiguing contraction, a compression of the sEMG power spectrum to a lower frequency is typically observed. Individuals with better endurance would exhibit a less precipitous decay of the median frequency (MF) [10–11]. The signals recorded by sEMG are the instantaneous algebraic summations of action potentials from muscle fibers. Fourier transformation is a linear analysis of a signal and gives the

Abbreviations: ANOVA = analysis of variance, BMI = body mass index, ES = erector spinae, FFT = fast Fourier transformation, LBP = low back pain, MF = median frequency, ODI = Oswestry Disability Index, SD = standard deviation, sEMG = surface electromyography.

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power spectrum $P(f)$ [12]. Several studies have suggested that sEMG power spectrum analysis, which is MF slope, could also be used to evaluate subjects undergoing rehabilitation [13–16]. However, previous studies reported conflicting results regarding the spectral sEMG measures of back muscle fatigue [17–20]. As we previously reported, the power spectrum calculated from the sEMG time series is not smooth and includes random noise superimposed on its background [21–23]. This phenomenon might explain the contradictory results of fatigue studies based on MF or its slope that are due to the noisiness of the power spectrum and indicate that the signal is not characterized by a single time scale.

Nonlinear analysis has proved to be useful in the analysis of a variety of physiological time series, such as human heartbeats [24–26] and the shapes of red blood cells under flow stress [27]. In particular, entropy is used to characterize nonperiodic random phenomena, including physiological time series, and indicates the rate of information production as it relates to dynamic systems [28]. Several research groups have compared entropy values for subjects with and without illness/dysfunction [26,29–32]. On the basis of these empirical studies, the time series from nondisabled subjects have been found to have higher entropy values than others. The results suggest that the absence of physiological complexity is related to pathology. On the basis of our previous studies, the entropy reveals properties of the sEMG signal that are not captured by the power spectrum; this finding suggests a possible benefit of entropy as a tool for the clinical assessment of LBP [21–23].

It is generally believed that subjects with musculoskeletal illness/dysfunction have lower endurance [23]. We reported that subjects with LBP have lower entropies than nondisabled subjects, which suggests that entropy relates to endurance [22]. Therefore, the primary purpose of the current study was to assess gender differences in back muscle fatigability in subjects with LBP based on MF slope and entropy. The second aim of this study was to assess the potential influence of anthropometric variables on MF slope and entropic measures.

METHODS

Selection of Subjects

The focus of this study was examination of muscle fatigability in the thoracic and lumbar portions of the erector

tor spinae (ES) muscles in subjects with LBP. Subjects in this study were recruited from the greater Cleveland area. Subjects with LBP were defined as those who had experienced a disturbing impairment or abnormality in the functioning of the low back for more than 2 months [33]. Subjects were eligible to participate if they (1) were 21 years of age or older, (2) had had LBP for more than 2 months without pain referral into the lower limbs, and (3) possessed a normal body mass index (BMI) value (18.5–24.9). Subjects were excluded from participation if they (1) had a diagnosed psychological illness that might interfere with the study protocol; (2) had difficulty understanding written/spoken English, which precluded them from completing questionnaires; (3) had experienced overt neurological signs (sensory deficits or motor paralysis); or (4) were pregnant. Participants were withdrawn from the study if they requested to withdraw. Those subjects who met study inclusion criteria received information regarding the purpose and methods of the study and signed a copy of the institutional review board-approved consent form.

Pain/Disability Level

Subject pain/disability was inferred from self-reported scores on the Oswestry Disability Index (ODI), which was given to each subject during the initial testing sessions. The ODI is one of the most frequently used tools for measuring chronic pain and disability [34]. A sum is calculated and presented as a percentage, where 0 percent represents no disability and 100 percent the worst possible disability [35–36].

sEMG Recording

We used the modified isometric fatigue test as originally introduced by Sorenson. Subjects were asked to lie in a prone position on a table and suspend their unsupported trunks horizontally against gravity while their lower bodies were strapped to the table at a 0° angle. The subjects' upper bodies were positioned with their iliac crests at the edge of the table; their lower bodies were secured at the ankles using seat belt straps. Subjects held their arms across their chests with each hand placed on the opposite shoulder and held a horizontal position until exhaustion. The test was discontinued once the participants could no longer maintain a horizontal position level to the table. The participants were allowed to reposition their upper bodies one time during the test, while standard verbalized encouragement was given throughout the test for all subjects.

The sEMG electrodes were placed bilaterally over the greatest convexity of the thoracic ES muscle at the L1–L2 level and the lumbar ES muscle at the L4–L5 level, with a 10 cm distance between electrodes of each pair. The electrode sites and the distances of the electrodes were carefully determined in each subject according to Zipp [37]. The sEMG data were collected using differential (interelectrode distance of 20 mm, with 8 mm diameter), preamplified (gain of 35), silver-silver chloride surface electrodes (Therapeutics Unlimited, Inc; Iowa City, Iowa) during the approximately 1-minute testing period. Data acquisition was performed using AcqKnowledge[®] software (BIOPAC Systems Inc; Goleta, California), with the resulting data analyzed in MathCAD (The MathWorks, Inc; Natick, Massachusetts). Using standard fast Fourier transformation (FFT) of the sEMG data, we obtained the power spectrum for each 1-second time interval.

During each 1-second interval, the sampling rate of the sEMG signals was 1,000 samples/second. The sEMG signals from the fatigue test were transformed into their frequency spectra using an FFT of the data. The MF of the signal was calculated from the spectrum for each 1-second time interval. Linear regression then gave the extrapolated value of the MF slope as well as the entropy scores during the 1-minute testing period.

The Shannon (information) entropy associated with the sEMG time series quantifies the “noisiness” of the signal. The detailed entropy calculation process was described in our previous studies [21,23]. Denoting V_t the voltage (in millivolts) at time t , we computed the sums of voltages for a time length t by

$$V_{t_0,t} = \sum_{j=0}^{t-1} v_{j+t_0} \quad (1)$$

For a given time t , we considered all the values $V_{t_0,t}$, which were distinguished from one another by the initial time t_0 . We divided the range of V in 500 equal bins of size $V = 0.1$ mV. At time t , using the histogram of V values, we estimated the probability distribution, $p_{j,t}$, and the entropy by

$$S_t = -\sum_j p_{j,t} \ln p_{j,t} \quad (2)$$

The dependence of S on t showed a plateau for $t > 10$ ms. The plateau value was then taken to represent the entropy (Figure 1).

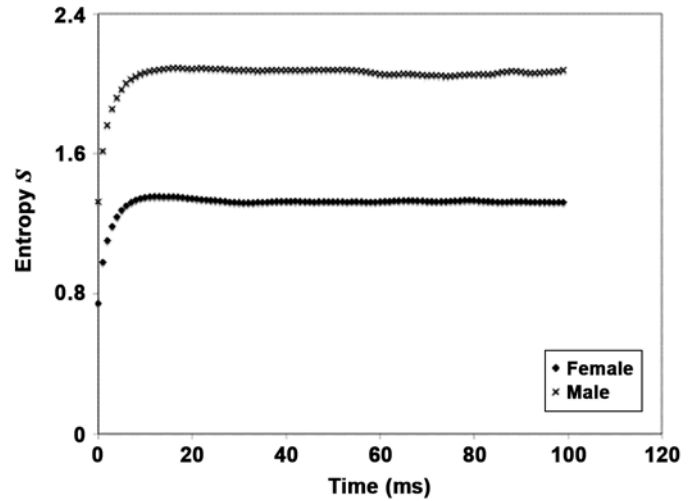


Figure 1.

Example of entropy values for right thoracic erector spinae muscles for each gender. The curves of entropy (dimensionless) versus time (ms) indicated that the Shannon entropy was higher in the male subject than in the female subject.

Statistical Analysis

We used descriptive statistics to compare the mean and standard deviation (SD) of each muscle group as well as subject characteristics. Assumptions of normal distribution of age, time since pain onset, level of pain/disability based on ODI scores, and the slope of MF versus time for the right and left thoracic and lumbar ES muscles were tested for the male and female groups. A t -test was then used to compare genders based on the MF slope and entropy level. The mixed repeated-measure analysis of variance (ANOVA) with respect to age, time since pain onset, and level of pain was conducted with the right and left thoracic and lumbar parts of the ES muscles. The entropy level and MF slopes were also compared between the thoracic and lumbar parts of the ES muscles. The nonlinear time series of sEMG data was analyzed based on entropy in order to compare any differences between subjects with LBP. The MathCad package (MathSoft; Cambridge, Massachusetts) was used for this analysis, which was loaded onto a personal computer running the Windows XP operating system (Microsoft Corp; Redmond, Washington). For all statistical tests, type I error rate was set at 0.05.

RESULTS

A total of 44 subjects with LBP enrolled in this study, with 24 female and 20 male subjects. As shown in Table 1,

the subjects ranged in age from 26 to 64 years, with an average age of 49.9 ± 9.4 years (all data are presented as mean \pm SD unless otherwise noted). The male subjects were slightly older than the female subjects, but no significant difference was found between genders ($p = 0.60$). In addition, no difference was found between genders based on the time since pain onset ($p = 0.45$) or ODI pain score ($p = 0.55$). Subject age and time since initial pain episode were not significantly correlated, with Pearson $r = -0.11$, $p = 0.47$. Therefore, no differences were found in anthropometric factors between genders.

In **Table 2**, the entropy level and MF slope were compared based on gender. Significant gender differ-

ences were found in entropy levels for the ES muscles, except for the right thoracic ES muscle. However, no gender differences were found based on the MF slope. These results were further analyzed by repeated-measure ANOVA as shown in **Figures 2** and **3**.

Table 3 shows the positive correlations that were found between entropy, gender, and the time since pain onset. The entropy level showed a significant correlation between gender and the left thoracic ES as well as both sides of the lumbar ES muscles. The time since pain onset had positive correlations with the entropy level of the left thoracic and right lumbar ($r = 0.41$ and 0.42 , respectively) ES muscles. However, no correlation was

Table 1.

Summary of subject demographics.

Variable	Males (<i>n</i> = 20)	Females (<i>n</i> = 24)	<i>t</i> -Value	<i>p</i> -Value
Age (yr)			-0.52	0.60
Range	40–63	26–64	—	—
Mean \pm SD	50.80 ± 8.77	49.29 ± 10.00	—	—
Time Since Pain Onset (mo)			-0.76	0.45
Range	4–24	4–17	—	—
Mean \pm SD	11.6 ± 5.6	10.4 ± 3.9	—	—
Oswestry Disability Index (%)			0.59	0.55
Range	20.2–38.0	20.0–36.1	—	—
Mean \pm SD	18.3 ± 10.9	20.4 ± 9.4	—	—

SD = standard deviation.

Table 2.

Gender differences in entropy and median frequency (MF) slope values for low back muscles.

Variable	<i>t</i> -Value	<i>p</i> -Value	Mean Difference	Standard Error Difference	95% Confidence Interval of Difference	
					Lower	Upper
Entropy						
R Thoracic ES	-1.486	0.15	-0.202	0.136	-0.479	0.075
L Thoracic ES	-2.165	0.04*	-0.218	0.100	-0.423	-0.012
R Lumbar ES	-2.607	0.01*	-0.306	0.117	-0.545	-0.067
L Lumbar ES	-3.081	0.004†	-0.375	0.121	-0.623	-0.127
MF Slope						
R Thoracic ES	1.332	0.19	0.056	0.042	-0.029	0.141
L Thoracic ES	1.534	0.14	0.057	0.037	-0.018	0.134
R Lumbar ES	0.275	0.79	0.018	0.067	-0.118	0.155
L Lumbar ES	-0.146	0.88	-0.009	0.066	-0.144	0.125

* $p \leq 0.05$.

† $p \leq 0.01$.

ES = erector spinae, L = left, R = right.

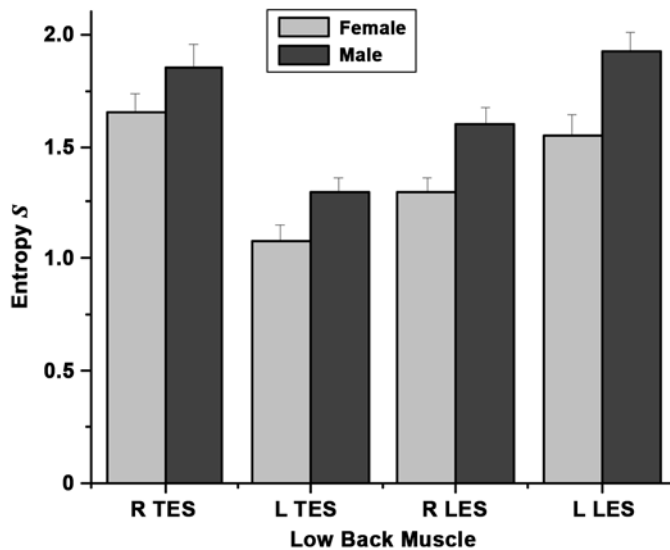


Figure 2.

Gender differences in entropy levels of the low back muscles. Entropy levels were significantly different between genders ($F = 6.70$, $p = 0.01$) as well as for the low back muscles ($F = 68.26$, $p = 0.001$). The male subjects demonstrated higher entropy levels than the female subjects. L = left, LES = lumbar erector spinae muscle, R = right, TES = thoracic erector spinae muscle.

found with age, pain level, or entropy level of the back muscles. **Table 4** shows the positive correlations that were found between pain level and MF slope, although the strength of these correlations was not high ($r = 0.41$ and 0.44 , respectively). The MF slope did not correlate with age, gender, or time since pain onset.

In **Figure 2**, the entropy level of the right thoracic ES muscle was 1.64 ± 0.39 for the female group and 1.84 ± 0.39 for the male group, while the entropy level of the left thoracic ES muscle was 1.08 ± 0.25 for the female group and 1.29 ± 0.33 for the male group. The entropy level of the right lumbar ES muscle was 1.29 ± 0.35 for the females and 1.60 ± 0.31 for the males, while the entropy level of the left lumbar ES muscle was 1.54 ± 0.38 for the female subjects and 1.92 ± 0.30 for the male subjects. The entropy level was significantly different between genders ($F = 6.70$, $p = 0.01$) as well between the low back muscles ($F = 68.26$, $p = 0.001$). Interactions between entropy level and other demographic variables were also found, such as age ($F = 0.38$, $p = 0.53$), time since pain onset ($F = 0.57$, $p = 0.46$), and ODI pain score ($F = 0.92$, $p = 0.34$), but these differences were not statistically significant.

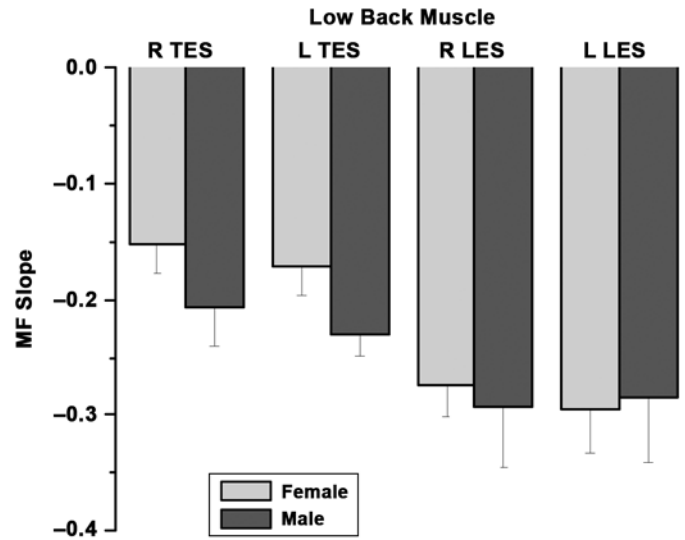


Figure 3.

Gender differences in median frequency (MF) slope of the low back muscles. Generally, steeper MF values (greater negative slope) indicated higher fatigability. Although the male subjects demonstrated steeper MF slope values, no significant difference was found between genders ($F = 0.44$, $p = 0.51$). L = left, LES = lumbar erector spinae muscle, R = right, TES = thoracic erector spinae muscle.

In **Figure 3**, the MF slope of the right thoracic ES muscle was -0.15 ± 0.12 for the female group and -0.21 ± 0.13 for the male group, while the MF slope of the left thoracic ES muscle was -0.17 ± 0.09 for the female group and -0.22 ± 0.12 for the male group. The MF slope of the lumbar ES muscle on the right side was -0.27 ± 0.16 for the female subjects and -0.29 ± 0.22 for the male subjects, while the left side was -0.29 ± 0.22 for the females and -0.28 ± 0.22 for the males. The MF slope was not significantly different between genders ($F = 0.44$, $p = 0.51$), and no interaction was found between gender and MF slope ($F = 1.74$, $p = 0.19$). However, a significant difference was found in the MF slope of the four low back muscles ($F = 21.33$, $p = 0.001$). In addition, the interaction between the MF slope and the demographic variables age ($F = 0.16$, $p = 0.68$), time since pain onset ($F = 0.12$, $p = 0.72$), and ODI pain score ($F = 1.32$, $p = 0.25$) were not statistically significant.

DISCUSSION

The purpose of this study was to assess gender differences in MF slope and entropy level for subjects with

Table 3.

Pearson correlation coefficients relating entropy with anthropometric variables.

Variable	R Thoracic ES	L Thoracic ES	R Lumbar ES	L Lumbar ES
Age	-0.285	-0.241	-0.241	-0.135
Gender	0.254	0.357*	0.419*	0.478 [†]
Time Since Pain Onset	0.195	0.415*	0.420*	0.300
Pain Level	-0.237	-0.186	-0.315	-0.332

* $p \leq 0.05$.[†] $p \leq 0.01$.

ES = erector spinae, L = left, R = right.

Table 4.

Pearson correlation coefficients relating median frequency slope with anthropometric variables.

Variable	R Thoracic ES	L Thoracic ES	R Lumbar ES	L Lumbar ES
Age	-0.034	0.153	0.055	0.115
Gender	-0.229	-0.262	-0.049	0.026
Time Since Pain Onset	0.134	0.176	0.101	0.184
Pain Level	0.443*	0.434 [†]	0.427 [†]	0.414 [†]

* $p \leq 0.01$.[†] $p \leq 0.05$.

ES = erector spinae, L = left, R = right.

LBP. While the MF slope was not different based on gender, the entropy measure results indicated that the male group had significantly higher values than the female group. Other anthropometric factors (e.g., age, gender, time since pain onset, and pain level) were not statistically significant based on MF slope and entropy measures. We point out, however, that the observed differences based on gender were smaller than the reported differences between nondisabled subjects and subjects with LBP from our previous study [23]. We reported, in particular, that the subjects without LBP had entropy levels $S > 2$, while subjects with LBP had levels $S < 2$. These findings demonstrated that healthier biological systems exhibit higher entropy levels [13–14]. The range of entropy values in our present study was $S < 2$ for both the male and female groups, which is in agreement with our earlier findings.

The results of our study based on MF slope showed no differences between male and female subjects [8,38]. It has been widely accepted that women have lower fatigue than men in most studies comparing the fatigability of the back muscles between genders [39–40]. A recent study indicated that men had a significantly higher rate of lumbar injury than women and that the women evidenced a higher rate of healthcare-seeking behaviors. In addition, the study also indicated that men showed

fewer depressive symptoms [41]. Men generally possess greater upper-body mass, whereas women have greater lower-body mass. Therefore, possible factors that might explain fatigability differences between genders are based on behavior and related potential influences of anthropometric variables.

Other studies comparing men with women through the Sorenson fatigue test reported lower fatigue measures in women as well [17,40,42–43]. For example, muscle physiology studies generally demonstrate higher muscular endurance in women [44–45]. Potential gender differences exist in daily activities, and numerous reports suggest that women have a greater muscular endurance capacity than men [40,44–48]. This could be attributed to the notion that women use a greater force-generating capacity than men [45]. However, other studies report conflicting results with lower fatigue shown in women using a mechanical muscle fatigue criterion [7–8,49]. For example, the MF of the lumbar extensors demonstrated a greater association with endurance time in men than in women, and the findings suggest that gender differences in muscle fatigue are influenced by frequency shifts in the sEMG signal [44]. The sEMG parameters based on MF slope may not be sensitive enough to differentiate back muscle fatigability [9].

In addition, differences were observed in the sEMG parameters across the force levels, but the sEMG parameters were insensitive to differences in back muscle strength [50]. Therefore, the present study was conducted in order to compare the physiological significance of entropy and MF slope since it has been reported to be unreliable over time and load-dependent [51]. In previous studies, we focused on the complexity of the sEMG signal and calculated the entropy of the time series. Our present study indicated higher entropy levels for males than for females. This result was somewhat unexpected since females were expected to have higher entropy levels based on their lower muscle fatigability. We propose that gender differences in entropy levels reported in this study reflect anthropometric differences between the two groups rather than fatigability differences. Further studies are necessary to address such effects.

The anthropometric variables were considered by correlation analysis with the entropy and MF slope. The overall correlation coefficients of the MF slope and pain level were not high enough ($r = 0.41$ and 0.44 , respectively), although they were statistically significant, to justify the relationship. The correlation coefficients between entropy and the time since pain onset also were not high enough to justify the relationship ($r = 0.19$ and 0.42 , respectively). As Portney and Watkins indicated, the significance of a correlation coefficient does not mean that a correlation coefficient represents a strong relationship [52]. Therefore, low correlations should not be discussed as clinically important just because they have achieved statistical significance. Clearly, the noisiness of the power spectrum indicates that the signal is not characterized by a single time scale. Although a positive correlation exists between pain level and MF slope in the back muscles, the statistical use of correlation coefficients based on several validation studies may be a poor choice for reliability studies [53]. However, differences are also possible in pain tolerance and fear-avoidance beliefs between genders [54]. In addition, our study did not evaluate osteoporosis, postmenopausal status, and the respective gravida para scores for women. We excluded subjects from participation if they had experienced overt neurological signs (sensory deficits or motor paralysis) or were pregnant. However, these factors could be considered as possible confounding factors that can be studied. Further studies are needed to consider the effects of anthropometric data on spectral and entropic measures for sEMG time series.

Clearly, the ability to localize sEMG signal sources deteriorated as the thickness of subcutaneous fat between the surface recording site and the active muscle fibers increased [55]. Since the plateau value of the entropy increases with the amplitude of the sEMG signal, other factors such as skinfold thickness could be considered. In our study, however, the subjects were not significantly different based on their BMI, and the sEMG recorded during a submaximal contraction of the back muscle became less highly affected based on skinfold thickness. Furthermore, our study did not address the reliability of both the spectral and entropic measures of sEMG time series since the signal was recorded only during a single testing session for each subject. However, it will be important in future studies to include larger sample sizes with matched anthropometric variables such as age, gender, pain level, body fat, height, family history, and/or time since pain onset, which might all account for individual variations.

CONCLUSIONS

Entropy is a measure of complexity, and the level of entropy was higher in the male subjects than in the female subjects with LBP in this study. A general physiological mechanism for the apparent correlation between entropy and pain/dysfunction is still unknown. However, the results of our research indicated that fatigability might be measured as entropy level in order to differentiate between genders.

Potential gender differences exist in the characteristics of activities related to musculoskeletal illness/dysfunction. However, the importance of the type of pain measure has received little consideration because different characteristics of the illness/dysfunction are already known to influence gender differences. Also, a possible connection exists between the entropy of physiological time series in sEMG in male subjects with LBP who demonstrated higher entropy values. The higher entropy evident in the lumbar ES muscles of the male subjects indicated the usefulness of nonlinear analysis of sEMG time series in a clinical assessment of LBP. The findings of the present study were consistent with previous studies as well, but further extensive and randomized controlled studies are needed to detect this possible cause and effect pattern regarding anthropometric variables with nonlinear time series analysis.

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The authors have declared that no competing interests exist.

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